ON THE DIFFERENTIAL ROTATION WITH HEIGHT IN THE SOLAR ATMOSPHERE*

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Abstract. Spectroscopic measurements of solar rotation having good height discrimination show no change in angular velocity through the photosphere layers but an increase of 8% for the Hα chromosphere (epoch 1968.9). Spectroscopic results in general are compared with measures made with tracers, i.e. sunspots, filaments, etc., and it is seen that the spectroscopic method always shows increased differential rotation with height, while tracers indicate none. A westward flowing wind is proposed that increases in velocity with height, but produces negligible movement to magnetic regions associated with tracers.

1. The Observations

Adams (1911), from observations in 1906–1908 of spectroscopic line shifts at the sun's equatorial limbs, discovered that the sun exhibits a differential rotation with height. The outer atmospheric layers appear to move forward over the lower with a higher angular velocity. Within the photosphere where the weaker Fraunhofer lines are formed, and which we now believe to be no more than about 200–300 km in extent (c.f. De Jager, 1959), Adams detected an increase of angular velocity outward of 1.5%. Discrimination with height through the photosphere was provided by comparing velocity shifts of the low-lying CN lines with that of strong Fe lines corresponding to upper layers. Data for Hα represented the chromosphere which we have taken as lying 2–3000 km above the photosphere. Hα yielded a velocity 2.5–4% over that of the photosphere.

Subsequent studies have confirmed in a general way Adam's results, although the quantitative details have differed. The observers have been Abetti and Novakova (1929), Evershed (1935), Perepelkin (1932), St. John and Babcock (1924) and more recently Aslanov (1963). Their findings are summarized in Table I. The listing emphasizes height effects, in distinction to other systematic differences, by indicating the percentage change within each observer's data.

Of special interest is this recent work of I. A. Aslanov. He carried out a major investigation of differential rotation within the photospheric layers. Limb measurements of 1700 lines were made. He plotted these limb shifts against the line parameters of wavelength, chemical element, excitation potential, equivalent width, and depth of formation. No correlation was found with wavelength, but proceeding through the above list the correlation improved, being best for depth of formation.

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TABLE I

Summary of results of measurement of change of angular velocity with height above the sun's surface

Observer	Epoch	Photosphere Source	$\Delta\omega$[a]	Chromosphere Source	$\Delta\omega$[a]
Adams	1906.4–1908.8	CN	−0.7%		
		Strong Fe	+0.7%		
	1908.3–1908.7			Hα limb	+ 4.0%
				Hα disk	+ 2.5%
Abetti, Righini	1928.8			$H\alpha_2$	− 0.5%
				$H\alpha_3$	+ 4.0%
				Other emission lines	+ 4.0%
Evershed	1926.7–1928.8			Ca^+K	+13.0%
	1929.2–1934.9			Ca^+K	+11.0%
	1931 –1934.9			Ca^+K	+10.0%
Perepelkin	1928 –1930			Ca^+K	≃ 0 %
St. John	(1910 –1924)			Ca^+K	+12.0%
				Hα	+ 6.0%
Aslanov	1960 –1961	Fe I, Ti I	−10%		
		$\Delta h \simeq 200$ km	+ 4%		
Author	1968.9	Fe I, C I	0%	Hα	+ 8.0%
		$\Delta h \simeq 150$ km	0%		

[a] $\Delta\omega = \frac{\omega_{\text{source}} - \omega_{\text{metal lines}}}{\omega_{\text{metal lines}}} \cdot 100\%$, where ω is the angular velocity of rotation.

Aslanov's measurements, based on Fe I and Ti I lines only, indicated the exceptionally large outward increase of 14%. Unfortunately he did not report on any chromospheric lines.

Our own observations (Livingston, 1969) have shown a 3–6% rate change between the photosphere and chromosphere, but have provided no depth sensitivity within the former. We report now on new rotation measurements designed to maximize height discrimination at all levels. To sense the lowest layers we chose the line C I 5380, which according to the contribution curves of Elste (1955) is formed at an optical depth $\tau = 0.9$. The high photosphere is represented by Fe I 5233 ($\tau \simeq 0.1$) while the chromosphere is given by Hα.

The results for December 30–31, 1968 are given in Figure 1. No appreciable difference in the equatorial rate is seen through the photosphere, but the chromosphere if found to be moving 8% faster. These results differ strongly from those of Aslanov. We remark that he studied a vast number of lines for a few places on the disk, while we have averaged many image points with but three selected lines. Each point plotted in Figure 1 represents the linear fit to several hundred spatial elements across the sun's disk (see the author's previous paper for a description of the observational method and their reduction). Because large scale currents obviously hinder the determination of the sun's rotation characteristics, we believe this use of many disk elements to be essential.

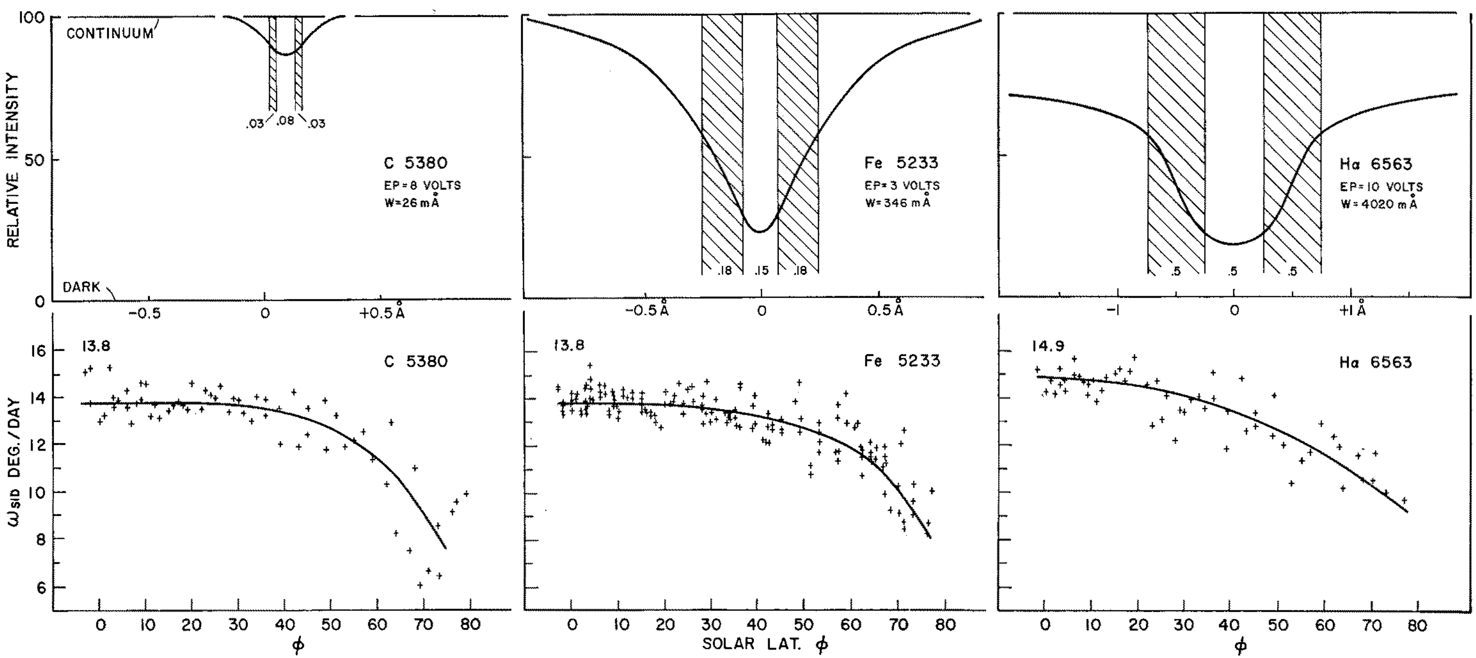

Fig. 1. Angular velocity as a function of heliographic latitude as determined on December 30–31, 1968 for different spectrum lines. How the various analyzing slits span the line profiles are shown in the upper diagram.

2. Discussion and Conclusions

Besides the spectroscopic data another kind of observational evidence should be mentioned when considering differential rotation with height: that provided by chromospheric tracers. Measurements of solar equatorial rotation based on the transit times of white-light faculae (Greenwich, 1924), the calcium K-network (Hale and Fox, 1908), and filaments (d'Azambuja, 1948) lead to angular velocities only slightly in excess of that given by sunspots (Newton and Nunn, 1951). Even coronal structures appear to rotate more or less synchronously with the sunspots (Trellis, 1957; Hansen *et al.*, 1969). In summary, the spectroscopic data favors a significant increase in velocity with height, while tracer measures provide uncertain or negative evidence.

It should be noted that the spectroscopic determinations are biased toward the quiet sun and disassociated from magnetic regions with their disturbing velocity patterns. On the other hand all tracer measures necessarily reflect the conditions imposed by the magnetic fields that are a part of these phenomena. The qualitative picture that emerges, then, is of a westward flowing wind that increases in velocity with height, but flows around, or produces negligible movement to magnetic regions.

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